


 Cite this: *RSC Adv.*, 2023, **13**, 12229

# Engineering S-scheme $\text{Ag}_2\text{CO}_3/\text{g-C}_3\text{N}_4$ heterojunctions sonochemically to eradicate Rhodamine B dye under solar irradiation

 Ali Alsulmi,<sup>a</sup> Mohamed H. Shaker,<sup>b</sup> Abanoob M. Basely,<sup>b</sup> M. F. Abdel-Messih,<sup>b</sup> Ayman Sultan<sup>c</sup> and M. A. Ahmed \*<sup>b</sup>

The use of natural solar radiation is a low-cost significant technology for water pollution remediation and production of clean energy. In this work, S-scheme  $\text{Ag}_2\text{CO}_3/\text{g-C}_3\text{N}_4$  heterojunctions were engineered for carefully eradicating Rhodamine B dye under natural sunlight irradiation. Solid thermal decomposition reactions generate  $\text{g-C}_3\text{N}_4$  sheets by annealing urea at 520 °C.  $\text{Ag}_2\text{CO}_3$  nanoparticles are directed and localized sonochemically to the active centers of  $\text{g-C}_3\text{N}_4$  sheets. The physicochemical properties of the solid specimen were determined by PL, DRS, XRD, HRTEM, mapping, EDX,  $\text{N}_2$ -adsorption-desorption isotherm and XPS analyses. As elucidated by HRTEM, PL and DRS analyses, 5 wt% of spherical  $\text{Ag}_2\text{CO}_3$  nanoparticles deposited on the  $\text{g-C}_3\text{N}_4$  sheet surface and nearly equidistant from each other elevate the electron-hole separation efficiency and broaden the absorption capacity of photocatalysts. Rhodamine B dye was degraded at a rate of  $0.0141 \text{ min}^{-1}$  by heterojunctions containing 5 wt%  $\text{Ag}_2\text{CO}_3$  and 95 wt%  $\text{g-C}_3\text{N}_4$ , which is three-fold higher than that on pristine  $\text{g-C}_3\text{N}_4$  nanosheets. Free radical scrubber experiments revealed the contribution of charge carriers and reactive oxygen species to the decomposition of RhB dye with a preferential role of positive holes and superoxide species. PL measurements of terephthalic acid and scrubber trapping experiments provide confirmatory evidence for charge diffusion *via* the S-scheme mechanism that accounts for the production of electron-hole pairs with strong redox power. This novel research work is contributory to manipulate the S-scheme heterojunction for efficient and low-cost wastewater treatment under natural solar irradiation.

Received 10th January 2023

Accepted 11th March 2023

DOI: 10.1039/d3ra00173c

[rsc.li/rsc-advances](http://rsc.li/rsc-advances)

## 1. Introduction

Water pollution is an environmental crisis that urgently needs to be addressed to meet the increasing demand for fresh water. Organic dyes are the major toxic pollutants discharged from different industries causing serious problems to human health and aquatic life.<sup>1–4</sup> Adsorption, reverse osmosis, electrochemical process, coagulation, enzymatic treatment and ion-exchange processes are very expensive, complicated techniques that produce a second generation of pollutant materials.<sup>5–10</sup> Photocatalysis on the surface of semiconductors is a green technology for the destruction of organic wastes into eco-friendly species. The photocatalytic reaction requires two factors to achieve optimization conditions. The first one is a low-cost and broadband solar radiation source that is sufficient to decompose millions of molecules of pollutants. The second requirement is an appropriate semiconductor with

tunable band gap energy and extremely high surface area that generates huge amounts of reactive oxygen species, which can destruct toxic pollutants in a short time under light irradiation. Natural sunlight in our country is very abundant in all seasons, particularly in summer days and acts as a low-cost radiation source. The natural sunlight contains a minor amount of UV radiation (5%), visible radiation (43%) and near infra-red (NIR) radiation (50%). Most of the previous research studies have focused on investigating the photocatalytic process under UV and visible light irradiation. In recent years, NIR is very effective in decomposing organic pollutants *via* photocatalytic and thermal routes. An appropriate semiconductor from the perspective of thermodynamics and kinetics must have the advantages of low cost, environmentally benign nature, high separation rate and fast transfer of charge carriers. Efficient semiconductors with wide bandgap structures as  $\text{TiO}_2$ ,  $\text{SnO}_2$ ,  $\text{ZnO}$  and  $\text{CeO}_2$  show high rate of organic pollutant decomposition<sup>11–16</sup> under UV irradiation that constitutes only 5% of the natural solar radiation. Narrow band gap energy semiconductors absorb visible light radiation; however, the ultra-fast electron-hole pair coulombic attraction decreased the life time required to generate reactive oxygen species.<sup>17–20</sup> In conclusion, a single semiconductor cannot achieve the

<sup>a</sup>Department of Chemistry, College of Science, King Saud University, P.O.2455, Riyadh, 11451, Saudi Arabia

<sup>b</sup>Chemistry Department, Faculty of Science, Ain Shams University, Egypt. E-mail: abdelhay71@hotmail.com

<sup>c</sup>Department of Chemistry, University of York, York YO10 5DD, UK


optimization properties for decomposing the organic pollutants. To overcome the limitations of single photocatalysts, heterojunctions composed of wide band gap energy with high efficiency for charge carrier separation and narrow band gap energy that harvests solar radiation are more favored. Recently, graphitic carbon nitride ( $g\text{-C}_3\text{N}_4$ ), has gained great interest in photocatalytic reactions due to its good stability in basic and acidic media, low synthesis costs, non-toxicity without side effects, sufficient biocompatibility, thermal stability, and a narrow band gap energy of about 2.7 eV and promote the photocatalytic activity under visible light.<sup>21–25</sup> Low specific surface area ( $\sim 50\text{ m}^2\text{ g}^{-1}$ ) and ultra-fast attraction of electron-hole pairs inhibit the prolonged time of charge carriers in the photocatalytic process. The low valence band potential ( $E_{\text{VB}} = +1.5\text{ eV}$ ) of  $g\text{-C}_3\text{N}_4$  fails to generate hydroxyl radicals ( $\cdot\text{OH}$ ), which are essential species for the destruction of organic pollutants. The hybridization of wide and narrow band gap energy semiconductors is a promising issue for successfully generating heterojunctions with appropriate solar radiation absorbability and high separation and transportation efficiency of electron-hole pairs. Silver-based photocatalysts such as AgCl,  $\text{Ag}_3\text{PO}_4$ ,  $\text{AgIO}_4$ ,  $\text{AgVO}_3$  and  $\text{Ag}_2\text{CO}_3$  exhibit strong photocatalytic reactivity in the decomposition of organic pollutants.<sup>26–31</sup> Much attention is drawn towards  $\text{Ag}_2\text{CO}_3$  nanoparticles due to their insolubility in water, low toxicity, adjustable bandgap structures and simple synthesis routes.<sup>32–41</sup> The successful construction of heterojunctions requires the appropriate adjustment of the band energy structure of the two semiconductors to generate charge carriers with an auspicious redox power.<sup>42–44</sup> Recent research studies have focused on coupling  $\text{Ag}_2\text{CO}_3$  with  $g\text{-C}_3\text{N}_4$  to generate a successful heterojunction for removing organic contaminants from wastewater.<sup>45–51</sup> Konglin *et al.* reported the successful photodegradation of Rhodamine B and methylene blue dyes over  $g\text{-C}_3\text{N}_4/\text{Ag}_2\text{CO}_3$  containing 3.5 wt%  $g\text{-C}_3\text{N}_4$ , which was ascribed to the predominant role of  $g\text{-C}_3\text{N}_4$  in limiting the electron-hole recombination.<sup>45</sup> Lei *et al.* synthesised  $g\text{-C}_3\text{N}_4/\text{Ag}_2\text{CO}_3$  containing 25 wt%  $g\text{-C}_3\text{N}_4$  *via* a sonochemical route for destructing RhB dye under a 300 W xenon lamp, and the experimental results manifested that  $g\text{-C}_3\text{N}_4$  increases the life time for charge carriers, which is responsible for the degradation process.<sup>46</sup> Shugang *et al.* prepared  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  containing 40%  $\text{Ag}_2\text{CO}_3$  by a co-precipitation process for removing methyl orange and methylene dyes. The remarkable reactivity of the nanocomposite was ascribed to the influence of  $\text{Ag}_2\text{CO}_3$  in enhancing the electron-hole transportation and separation.<sup>48</sup> Yun Feng *et al.* prepared  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  containing 30%  $\text{Ag}_2\text{CO}_3$  by a precipitation method for the removal of methyl orange and methylene blue. The exceptional reactivity is attributed to the role of  $\text{Ag}_2\text{CO}_3$  in enhancing the efficiency of charge carrier separation. Previous research studies concentrated on doping silver carbonate as a major constituent with  $g\text{-C}_3\text{N}_4$ , which is considered a high-cost route for water treatment. In this work, we made an attempt to construct S-scheme  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  with a minimum amount of silver carbonate. The previous research explores the construction of  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  *via* type (II) heterojunctions and direct Z-scheme

mechanism. The type (II) heterojunction fails from dynamic, thermodynamic and energetic points of view to explain the actual charge transportation. The electron transfer from high to low conduction band is accompanied by repulsion force between the existing and the transferring electrons. Concurrently, the electron diffusion from high to low energy level dissipates electrons with a strong reducing power. Direct Z-scheme fails to explain the precise analysis of charge migration between the two semiconductors. The construction of S-scheme  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  heterojunctions has not been explored in previous research studies. Hybridizing  $\text{Ag}_2\text{CO}_3$  with high positive oxidative potential and  $g\text{-C}_3\text{N}_4$  with high negative reductive potential generate successful S-scheme heterojunctions. The Fermi level and conduction band of  $g\text{-C}_3\text{N}_4$  is higher than those of  $\text{Ag}_2\text{CO}_3$ ; however, the work function of  $\text{Ag}_2\text{CO}_3$  is greater than that of  $g\text{-C}_3\text{N}_4$ . Upon light illumination, the Fermi levels of  $\text{Ag}_2\text{CO}_3$  and  $g\text{-C}_3\text{N}_4$  jump upward and downward until the two Fermi levels are contacted at the interface region. At this contact point, the electrons and holes with low redox potential are attracted toward each other, and vanished leaving a strong internal electric field. Concurrently, the holes and electrons in the higher valence and conduction bands with a strong redox power are consumed in the photocatalytic process. The production of S-scheme systems is more favorably engineered *via* a solution-based approach to control and tune the particle structure and pore matrix. The sonochemical route is a professional solution process for the synthesis of  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  heterojunctions with the homogeneous location of  $\text{Ag}_2\text{CO}_3$  on  $g\text{-C}_3\text{N}_4$  active centers. The as-synthesized heterojunction was subjected to decomposition of Rhodamine B under solar irradiation to utilize UV, visible and near infra-red radiations. Exclusively, NIR light elevates the reaction temperature through the photothermal effects, which enhances the photocatalytic activity. In this work, we aimed to synthesise  $g\text{-C}_3\text{N}_4$  from microcrystalline urea *via* a thermal decomposition process.  $\text{Ag}_2\text{CO}_3$  nanoparticles were hybridized with  $g\text{-C}_3\text{N}_4$  sheets in an ultrasonic bath of 300 W intensity. The physicochemical properties of the solid specimens were characterized by XRD, FTIR, HRTEM, EDX, XPS, mapping,  $\text{N}_2$  adsorption-desorption isotherm, DRS and PL analyses. The photocatalytic activity of the heterojunctions was explored by following the degradation of Rhodamine B dye under natural sunlight radiation of 500 W intensity. The key role of the oxygen radicals and charge carriers was elaborated by carrying out various trapping scavenger experiments and following the PL analysis of terephthalic acid as a probe radical material. On the basis of DRS, PL and trapping scavenger analyses, a proposed mechanism for the transportation of charge carriers between  $\text{Ag}_2\text{CO}_3$  and  $g\text{-C}_3\text{N}_4$  semiconductors in the circuit of the heterojunction is illustrated.

## 2. Materials and methods

### 2.1. Material

Isopropanol, urea, sodium carbonate, methanol, silver nitrate, benzoquinone, ammonium oxalate, Rhodamine B dye and terephthalic acid were supplied by Sigma-Aldrich Company.



## 2.2. Preparation of g-C<sub>3</sub>N<sub>4</sub> nanosheets

g-C<sub>3</sub>N<sub>4</sub> sheets were synthesized from urea after purification *via* recrystallization by 200 mL of methanol (99%) with continuous

stirring at 150 °C. The solution was allowed to stand at room temperature to get rid of volatile methanol carefully. Then, 100 g of recrystallized urea was annealed in a reactor made of

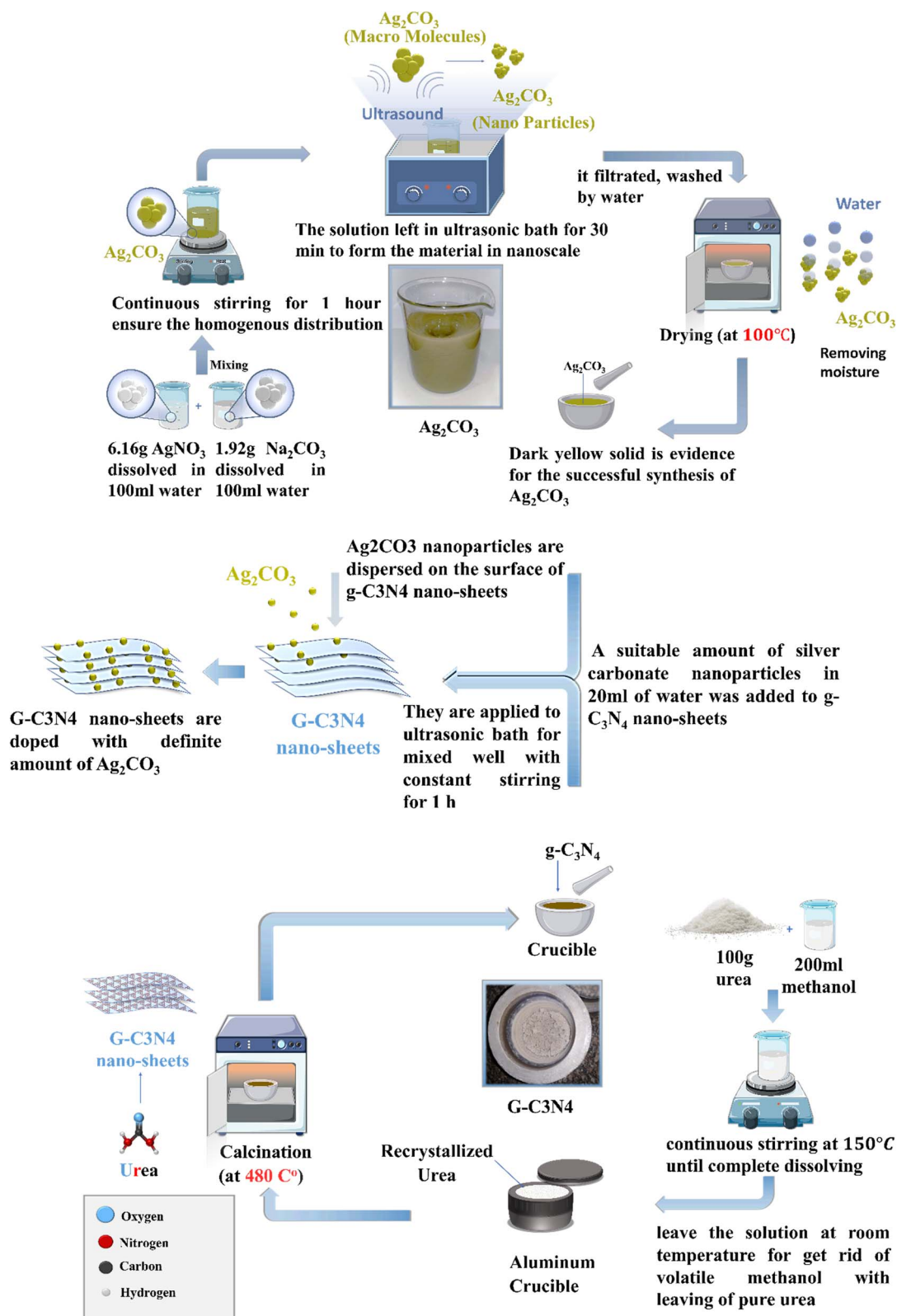


Fig. 1 Scheme for the synthesis of Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> nanocomposites.



aluminum metal at 520 °C for 3 hours and the obtained solid was washed with distilled water and dried at 80 °C. Finally, a yellow solid specimen was obtained and ground in a porcelain mortar to generate g-C<sub>3</sub>N<sub>4</sub> nanosheets.

### 2.3. Preparation of Ag<sub>2</sub>CO<sub>3</sub> nanoparticles

First, 6 g AgNO<sub>3</sub> dissolved in 100 mL distilled water was added to a solution containing 2 g Na<sub>2</sub>CO<sub>3</sub> dissolved in 100 mL distilled water with continuous stirring for 1 hour to ensure homogenous distribution. The solution was sonicated for 30 min in an ultrasonic bath at 300 W intensity followed by filtration, washing with distilled water and drying at 110 °C. A dark yellow solid was obtained, ground and stored in a falcon tube.

### 2.4. Preparation of Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> nanocomposites

Fig. 1 illustrates the plausible scheme for the synthesis of S-scheme Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> heterojunctions *via* a sonochemical route. Typically, a definite amount of silver carbonate nanoparticles dispersed in 20 mL of distilled water were sonicated with g-C<sub>3</sub>N<sub>4</sub> nanoparticles for 30 min by certain ratio to obtain (5, 10 and 20 w/w%) Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub>. After a while, each of the solution mixture was stirred for 1 h, filtered, washed with distilled water and dried at 80 °C. The photocatalysts are denoted as g-C<sub>3</sub>N<sub>4</sub>, Ag<sub>2</sub>CO<sub>3</sub>, CNAg5, CNAg10 and CNAg20 for pristine g-C<sub>3</sub>N<sub>4</sub>, pristine Ag<sub>2</sub>CO<sub>3</sub> and the heterojunctions containing 5, 10 and 20 wt% Ag<sub>2</sub>CO<sub>3</sub>, respectively.

### 2.5. Material characterization

A PANalytical X'PERT MPD diffractometer with Cu [Kα<sub>1</sub>/Kα<sub>2</sub>] radiation was employed to investigate the crystalline properties of the as-synthesized heterojunctions. FTIR spectroscopy revealed the functional groups of the nanocomposite samples. Adsorption isotherms of N<sub>2</sub> at 77 K precisely investigated the surface parameters and pore structure of the solid specimens. HRTEM (JEOL 6340) visualized the particle size distribution of Ag<sub>2</sub>CO<sub>3</sub> on the sheets of g-C<sub>3</sub>N<sub>4</sub>. A K-ALPHA (Thermo Fisher Scientific, USA) instrument with monochromatic X-ray Al Kα radiation in the range of 10–1350 eV was used for XPS analysis. JASCO spectroscopy (V-570) was performed to analyze the diffuse spectrum of the photocatalyst and determine the band energy structure. A lumina fluorescence spectrometer (Thermo Fisher Scientific) was used to analyze the efficiency of photo-generated electron-hole separation.

### 2.6. Photocatalytic degradation of RhB dye

Typically, 0.1 g of the photocatalyst is mixed with 100 mL of 10 mg L<sup>-1</sup> RhB dye in a solar reactor. The suspension was continuously stirred for 1 hour in the darkness until adsorption/desorption equilibrium was reached. After a while, the mixture solution was exposed to natural sunlight (450 W) at about 3 p.m. (Aug. 2021) for two hours. Then, 4 mL of the mixture was collected at definite time intervals, and then the photocatalyst was separated by centrifugation at 4000 rpm for 10 min. The photocatalytic degradation progress was followed

by tracing of the reduction of dye color intensity using a UV-visible spectrophotometer. The photocatalytic mechanism and nature of reactive species were investigated using free radical scrubbers such as AgNO<sub>3</sub>, isopropanol, ammonium oxalate and benzoquinone for detecting conduction band electrons, hydroxyl radicals, holes and superoxide radicals. The photoluminescence of terephthalic acid was investigated to monitor the production of hydroxyl radicals at an excitation wavelength of 325 nm.

## 3. Results and discussions

XRD spectrum explores the crystalline structure of pristine g-C<sub>3</sub>N<sub>4</sub>, Ag<sub>2</sub>CO<sub>3</sub>, CNAg5, CNAg10 and CNAg20 nanocomposites [Fig. 2]. Prevailing diffraction peaks of g-C<sub>3</sub>N<sub>4</sub> were recorded at 13.2 and 27.59°, which were ascribed to the (100) and (002) diffraction planes (JCPDS no. 87–1526). However, the diffraction peaks recorded at 17.8°, 20.1°, 31.9°, 32.7°, 36.5°, 38.8°, 41.1°, 43.7°, 46.5° and 50.9° were ascribed to Ag<sub>2</sub>CO<sub>3</sub> (JCPDS No. 23–0339) in the monoclinic crystalline structure. The Debye–Scherrer equation records that the crystalline size is 23.5, 30.7, 8.5, 7.3 and 6.5 nm for g-C<sub>3</sub>N<sub>4</sub>, Ag<sub>2</sub>CO<sub>3</sub>, CNAg5, CNAg10 and CNAg20 nanoparticles, respectively. The XRD pattern of the CNAg5 nanocomposite containing 5 wt% Ag<sub>2</sub>CO<sub>3</sub> resembled the diffraction pattern of g-C<sub>3</sub>N<sub>4</sub> with complete missing of the diffraction peaks assigned to Ag<sub>2</sub>CO<sub>3</sub>, revealing the homogeneous dispersion of Ag<sub>2</sub>CO<sub>3</sub> between g-C<sub>3</sub>N<sub>4</sub> sheets. The prevailing diffraction peaks assigned to monoclinic Ag<sub>2</sub>CO<sub>3</sub> were vividly recorded in the nanocomposites containing 10 and 20 wt% Ag<sub>2</sub>CO<sub>3</sub>. The chemical interaction between g-C<sub>3</sub>N<sub>4</sub> and Ag<sub>2</sub>CO<sub>3</sub> was investigated by the FTIR spectrum. In Fig. 3a, the spectrum of g-C<sub>3</sub>N<sub>4</sub> shows various peaks in the range of 1100–1700 cm<sup>-1</sup> assigned to the stretching vibration of heterocyclic C–N and C=N bonds and

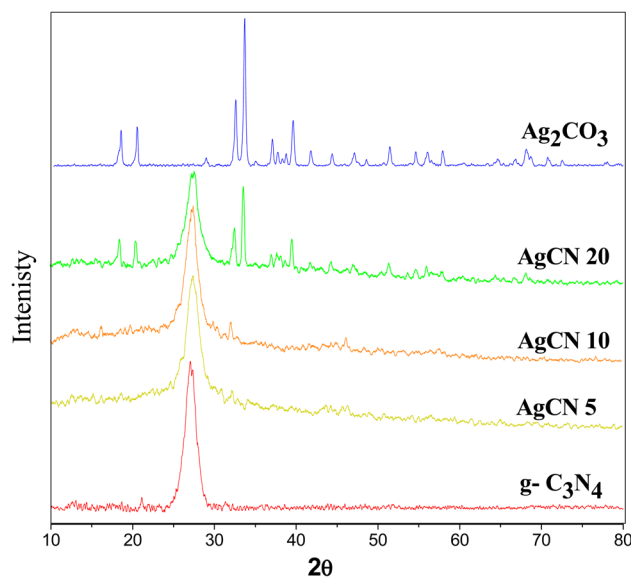


Fig. 2 (a) XRD pattern of g-C<sub>3</sub>N<sub>4</sub>, Ag<sub>2</sub>CO<sub>3</sub>, CNAg5, CNAg10 and CNAg20.





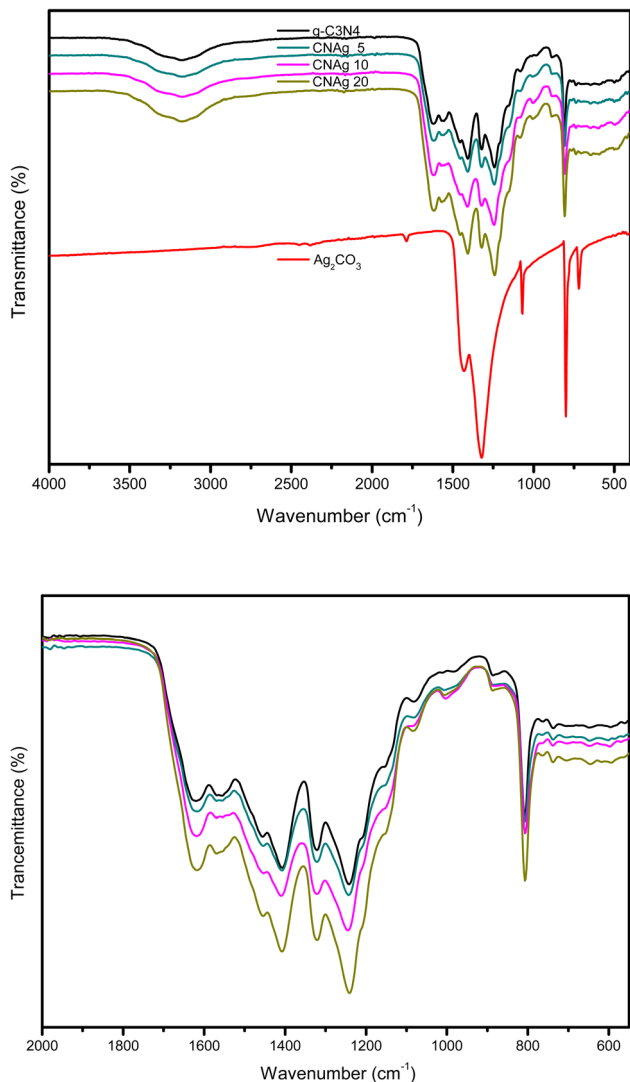


Fig. 3 FTIR spectra of  $g\text{-C}_3\text{N}_4$ ,  $\text{Ag}_2\text{CO}_3$ , CNAg5, CNAg10 and CNAg20 nanocomposites.

the peak at  $808\text{ cm}^{-1}$  is attributed to the triazine units, and the broad peak in the range of  $3000\text{--}3500$  corresponds to N–H and O–H bonds of physically adsorbed water. For the spectrum of  $\text{Ag}_2\text{CO}_3$ , four peaks were found at  $720$ ,  $800$ ,  $1320$ , and  $1430\text{ cm}^{-1}$ , indicating the presence of the  $\text{CO}_3^{2-}$  group.  $\text{N}_2$ -adsorption–desorption isotherms of pristine  $g\text{-C}_3\text{N}_4$  and CNAg5 were classified as type (II) with a closed hysteresis loop, which was ascribed to the non-porous structure [Fig. 4]. The surface area of  $g\text{-C}_3\text{N}_4$  and CNAg5 is  $55.5$  and  $44.3\text{ m}^2\text{ g}^{-1}$  according to the BET equation in its normal range of applicability. The existence of such open surface prohibits the photocatalytic reaction with unrestricted accommodation of pollutant molecules. However, porous systems restrict the diffusion and transportation of RhB molecules due to the pore constrictions. The HRTEM image of the CNAg5 heterojunction is represented in Fig. 5, which records the generation of  $g\text{-C}_3\text{N}_4$  sheets with laminar structure containing various wrinkle points. On careful exploration of HRTEM images at different magnifications, one can notice the successful deposition of spherical  $\text{Ag}_2\text{CO}_3$  nanoparticles on the active sites of  $g\text{-C}_3\text{N}_4$  sheets at equidistant positions in the homogeneous arrangement, which reveals the strong chemical interaction between  $\text{Ag}_2\text{CO}_3$  nanoparticles and  $g\text{-C}_3\text{N}_4$  sheets. The particle size distribution was elucidated by constructing histograms that reveal that major nanoparticles exhibit a size varying between  $15$  and  $20\text{ nm}$ . HRTEM records the existence of lattice fringes of spacing  $0.315\text{ nm}$ , which were ascribed to the (100) plane of  $\text{Ag}_2\text{CO}_3$ . SAED analysis manifests the existence of different rings ascribed to the crystalline planes of  $g\text{-C}_3\text{N}_4$  and  $\text{Ag}_2\text{CO}_3$  nanoparticles. Mapping and EDX elemental analysis results are illustrated in Fig. 6, revealing the uniform distribution of C, N, Ag and O in the CNAg5 heterojunction. The production of porous graphitic carbon nitride sheets with spongy structure was clearly observed with the homogeneous distribution of  $\text{Ag}_2\text{CO}_3$  on the localized active sites on  $g\text{-C}_3\text{N}_4$  sheets. The oxidation state and elemental distribution of the

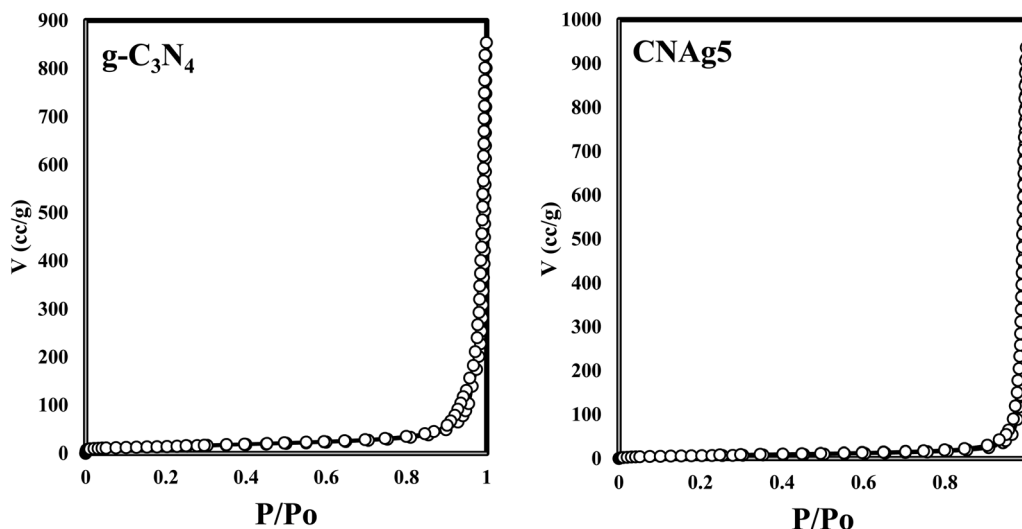


Fig. 4  $\text{N}_2$ -adsorption–desorption isotherms of  $g\text{-C}_3\text{N}_4$  and CNAg5.



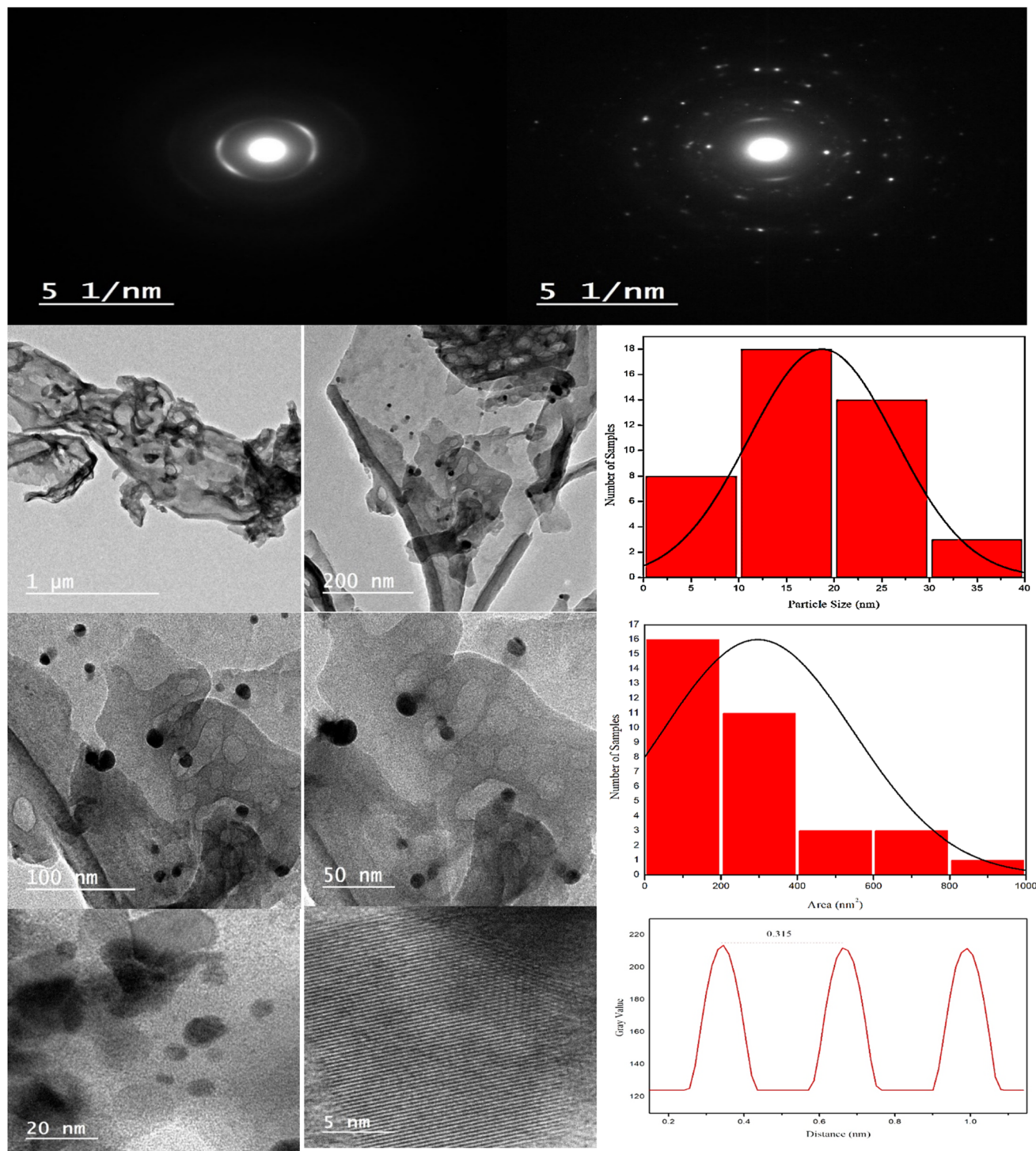


Fig. 5 HRTEM image and SAED pattern of CNAg5.

heterojunction constituent was investigated by XPS analysis [Fig. 7]. The spectrum indicates the existence of Ag, O, C and N with a perspective binding energy, revealing the high purity of the nanocomposite without the existence of any contaminant from the preparation medium. At binding energies of 367 eV and 373 eV, Ag (3d) was detected, which deconvoluted into Ag 3d<sub>5/2</sub> and Ag 3d<sub>3/2</sub>, respectively, having a spin-orbit separation of *ca.* 6.0 eV as detected in the previous research studies. The C

1s signal was resolved into three different peaks at 284.28 eV, 287.68 eV and 293.28 eV, corresponding to the C-C bonding states of surface carbon, sp<sup>2</sup>-bonded C (N-C=N) groups and carbonate (CO<sub>3</sub><sup>2-</sup>) groups from Ag<sub>2</sub>CO<sub>3</sub>. The broad peak of the N 1s spectra was resolved into four peaks at 398.6, 399.8, 400.4 and 403.9 eV, assigned to C-N-C, N-(C)<sub>3</sub>, C-NH<sub>x</sub>, and π excitation, respectively. Moreover, the characteristic peak of O 1s was deconvoluted into three peaks at 530.1 eV, 531.8 and





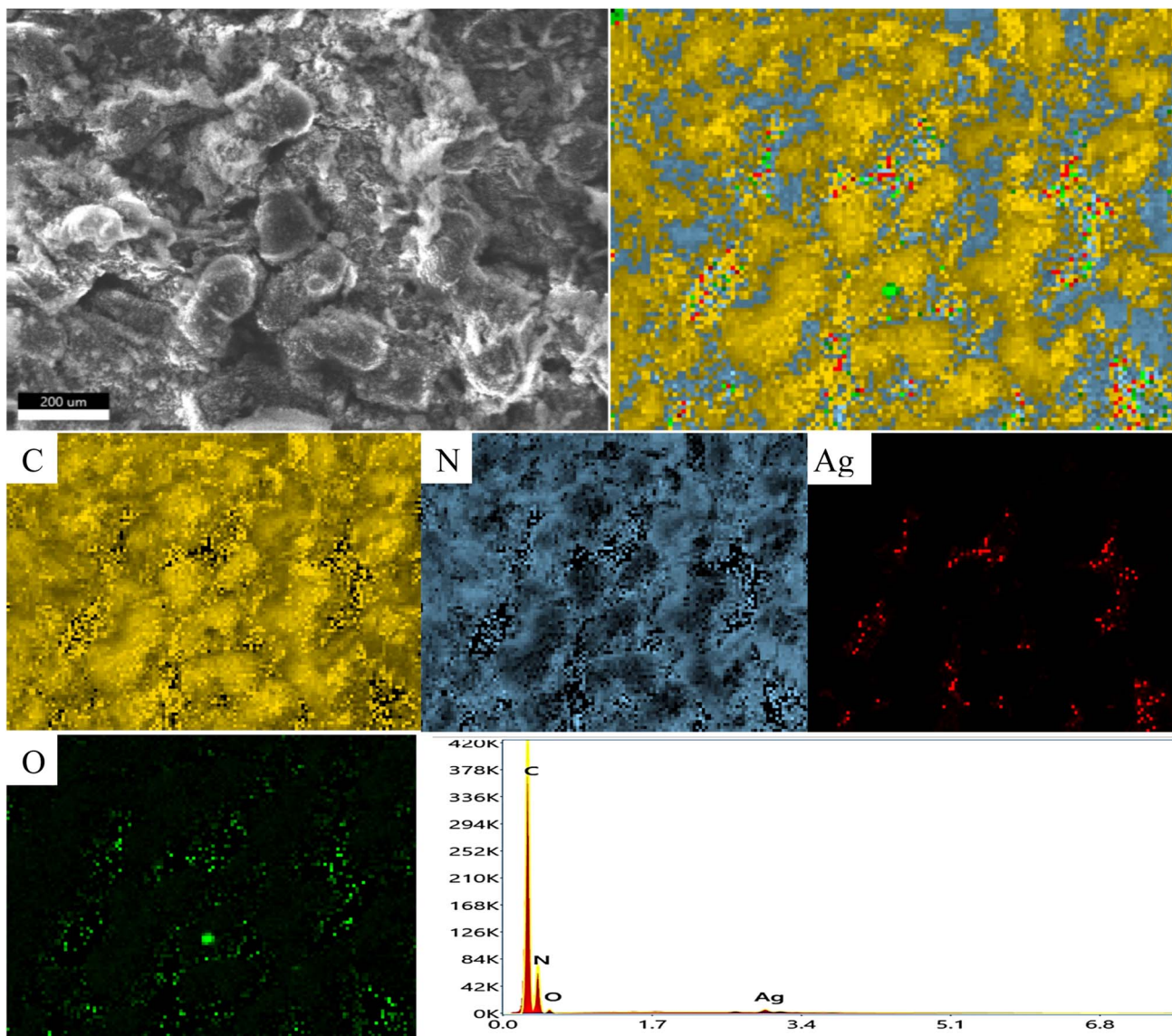


Fig. 6 Mapping and EDX spectrum of CNAg5.

532.8 eV which were ascribed to the C–O and C=O bonds in  $\text{Ag}_2\text{CO}_3$  and the surface of composite adsorbed –OH groups. The color of the nanocomposite became darker upon the incorporation of various contents of silver carbonate, revealing the shifting in the solid specimen's response to the visible light absorbability. Fig. 8 illustrates the DRS analysis of pristine  $\text{g-C}_3\text{N}_4$ ,  $\text{Ag}_2\text{CO}_3$  and  $\text{Ag}_2\text{CO}_3/\text{g-C}_3\text{N}_4$  heterojunctions. The band gap energy was calculated according to the Tauc equation to determine the type of the electronic transition. The shifting in light absorbability of  $\text{g-C}_3\text{N}_4$  from 420 to 470 nm is sufficient to enhance the photocatalytic reactivity of the solid specimen in the visible light region. The valence and conduction band potentials were calculated on the basis of band gap energy and the electronegativity of  $\text{g-C}_3\text{N}_4$  and  $\text{Ag}_2\text{CO}_3$ . The valence and conduction band potentials of  $\text{g-C}_3\text{N}_4$  are +1.57 and –1.13 eV. However, the valence and conduction band potentials of  $\text{Ag}_2\text{CO}_3$  are +2.55 and +0.45 eV. The

electron–hole separation efficiency for single-phase  $\text{g-C}_3\text{N}_4$  and the as-synthesized heterojunctions was explored by constructing the PL spectrum of solid specimens [Fig. 9]. A fantastic emission signal at an intensity of 445 nm belongs to the electron–hole coulombic attraction recorded in the PL spectrum. About 40, 45, 68 and 73% reduction in the PL peak intensity was detected with the introduction of 5, 10, 15 and 20 wt%  $\text{Ag}_2\text{CO}_3$  on the  $\text{g-C}_3\text{N}_4$  surface. These results clearly indicated the significant role of  $\text{Ag}_2\text{CO}_3$  in decreasing the electron–hole coulombic attraction force as well as promoting strong interactions between  $\text{Ag}_2\text{CO}_3$  and  $\text{g-C}_3\text{N}_4$ .

#### 4. Photocatalytic degradation of Rhodamine B dye

The ubiquitous existence of dyes and antibiotics in wastewater is an alarming environmental issue that affects human health



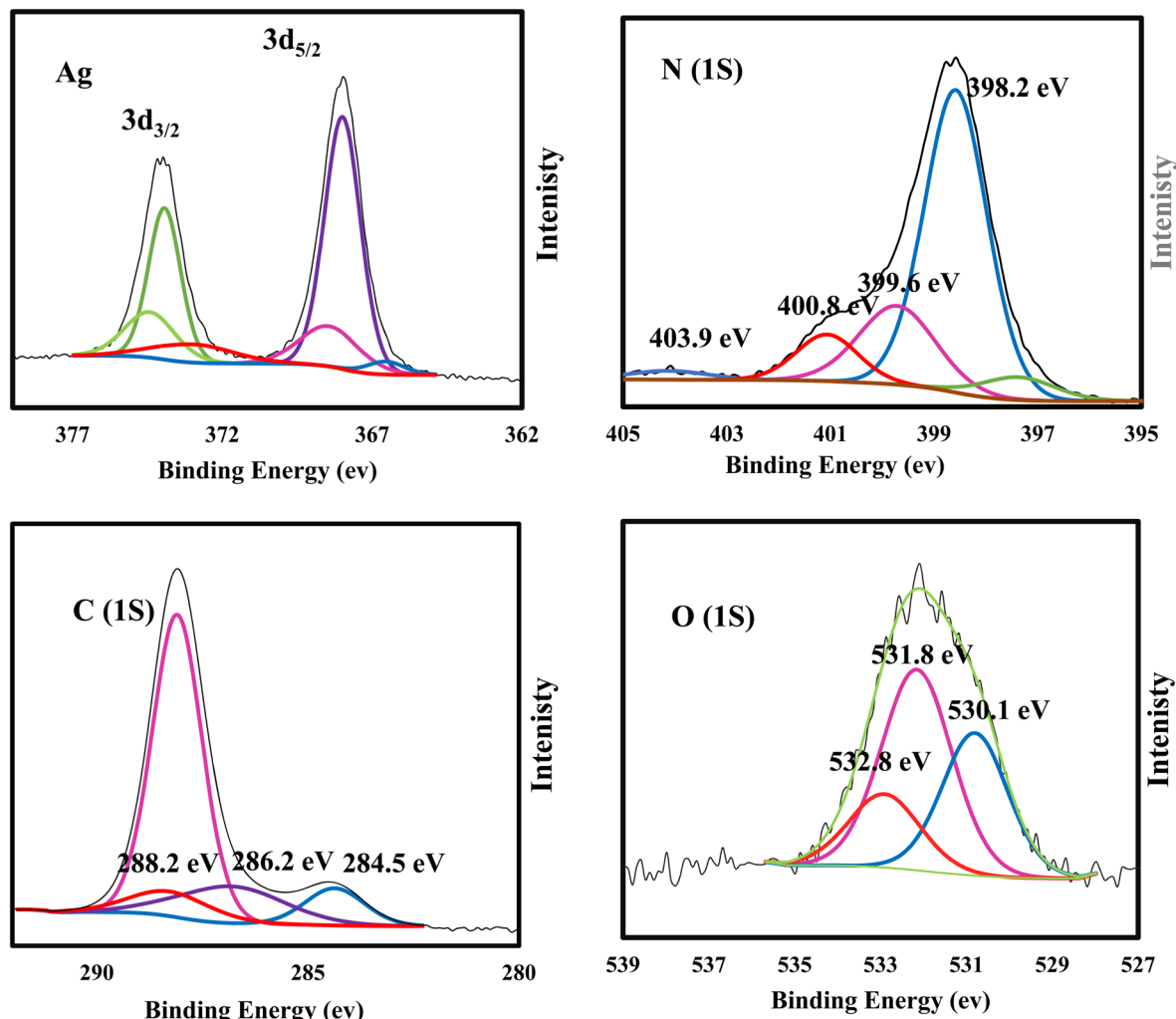


Fig. 7 XPS spectra of C, O, N and Ag in CNAg5.

and aquatic life. Among the industrial dyes, Rhodamine B is one of the most employed dyes in industries. Rhodamine B dye (RhB) is toxic, carcinogenic, and non-biodegradable that poses a serious threat to human health. Various routes were developed for the safe destruction of RhB dye into eco-friendly species without producing a secondary generation of pollutants. Photocatalytic destruction of RhB under natural solar irradiation into  $\text{CO}_2$ , water and small molecules is an auspicious route for expelling RhB dye from wastewater. The efficiency of the as-synthesized heterojunctions in degrading RhB was tested and compared under natural sunlight irradiation [Fig. 10] to investigate the influence of change in silver carbonate concentration on the efficiency of  $\text{g-C}_3\text{N}_4$  sheets. The decomposition of Rhodamine B dye under natural sunlight irradiation in the absence of photocatalysts is negligible due to the strong chemical stability of the dye solution. Pristine  $\text{g-C}_3\text{N}_4$  sheets exhibit poor efficiency in degrading RhB dye due to the ultra-fast recombination rate of electron-hole pairs and mild absorption responsibility under solar irradiation. On the contrary, pristine  $\text{Ag}_2\text{CO}_3$  shows high efficiency in degrading RhB dye, which results from the matching in band gap energy

with sunlight absorbability. However, the high cost of the silver precursor hampers the industrialization of  $\text{Ag}_2\text{CO}_3$  for wastewater treatment. The incorporation of small amounts of  $\text{Ag}_2\text{CO}_3$  on the surface of low-cost semiconductors is a promising route for the manipulation of efficient heterojunctions with a strong redox power. Compared with pristine  $\text{g-C}_3\text{N}_4$ , the heterojunctions containing 5, 10, and 20 wt% recorded a fast rate of dye decomposition that reached 95% of the dye initial concentration on the surface of heterojunctions containing 5 wt%  $\text{Ag}_2\text{CO}_3$  [Fig. 11a]. The decomposition of RhB dye passes through several intermediates generated by the expelling of the ethyl groups one by one. This process is trusted by observing various absorption peaks at different wavelengths arranged in descending order. The process of de-ethylation of the fully  $N,N,N',N'$ -tetra-ethylated Rhodamine molecule generates different intermediates as  $N,N,N'$ -tri-ethylated Rhodamine,  $N,N'$ -di-ethylated Rhodamine, and  $N$ -ethylated Rhodamine at 540, 522 and 502 nm, respectively. The rate of pseudo first order of the dye degradation is 0.0012, 0.0434, 0.0141, 0.0123 and 0.0098 over  $\text{g-C}_3\text{N}_4$ ,  $\text{Ag}_2\text{CO}_3$ , CNAg5, CNAg10 and CNAg20, respectively [Fig. 11b]. The kinetic results indicated that the





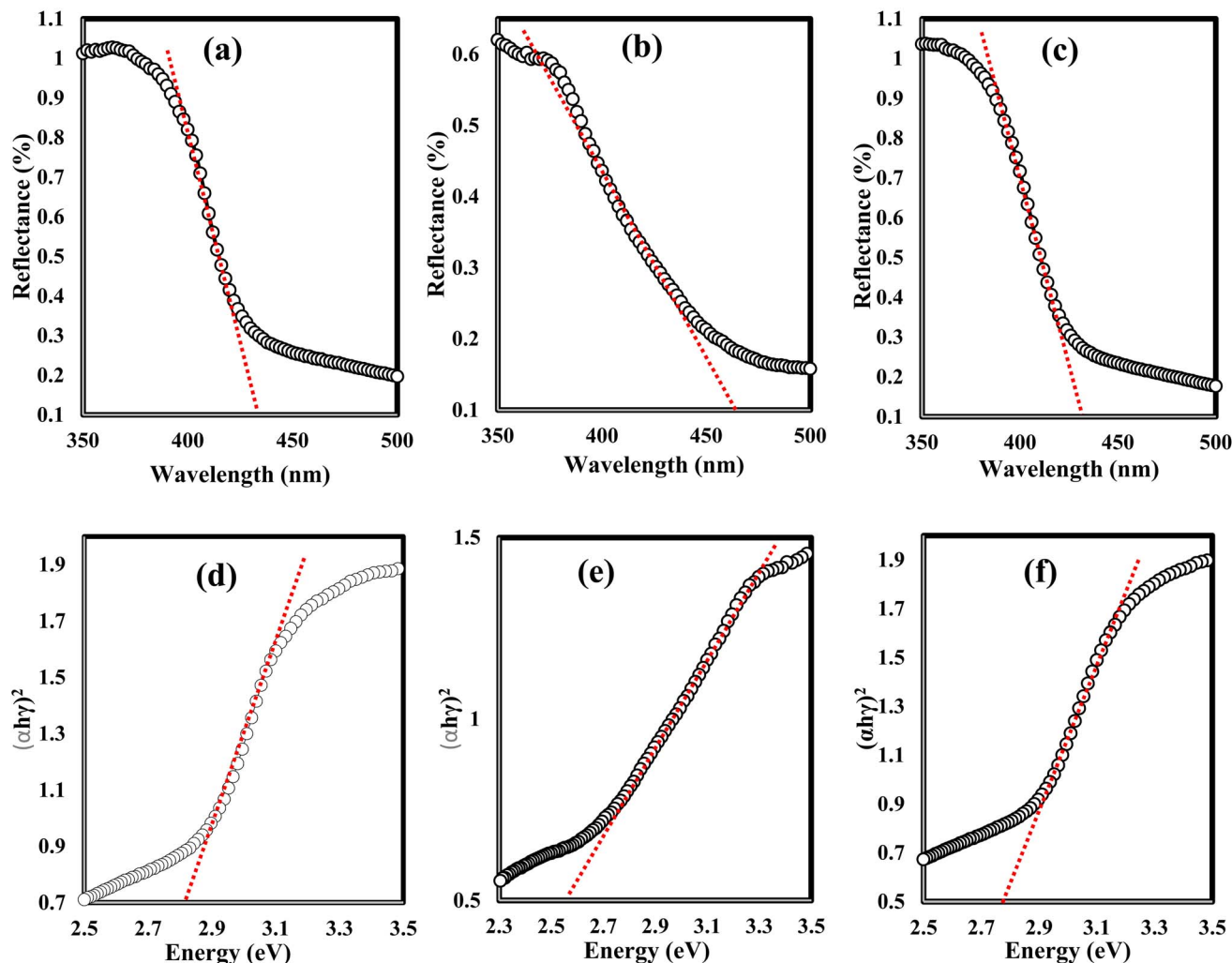


Fig. 8 DRS spectra of (a)  $g\text{-C}_3\text{N}_4$ , (b)  $\text{Ag}_2\text{CO}_3$ , and (c) CNAg5 nanoparticles. Tauc plots of (d)  $g\text{-C}_3\text{N}_4$ , (e)  $\text{Ag}_2\text{CO}_3$ , and (f) CNAg5 nanoparticles.

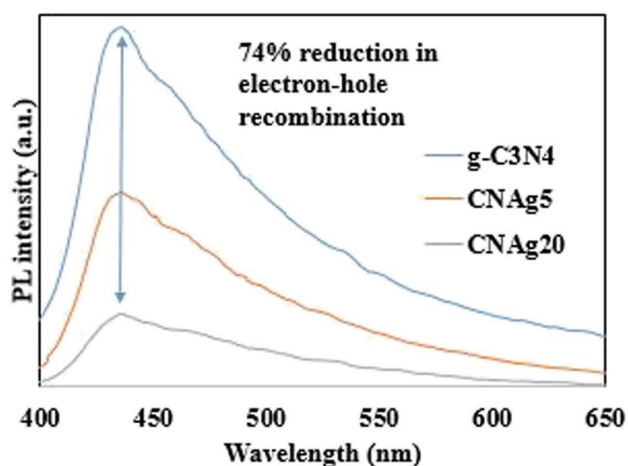


Fig. 9 PL spectra of  $g\text{-C}_3\text{N}_4$ ,  $\text{Ag}_2\text{CO}_3$ , CNAg5, CNAg10, and CNAg20.

rate of dye degradation over CNAg5 is fourfold higher than that on pristine  $g\text{-C}_3\text{N}_4$ . Scrubber trapping experiments using benzoquinone, isopropanol, ammonium oxalate and silver nitrate

were carried out to explore the role of superoxide and hydroxyl radicals besides the positive hole and electron conduction band on the destruction of RhB dye. The experimental result recorded a preferential retardation in RhB dye mineralization in the presence of benzoquinone, isopropanol and ammonium oxalate, which directed the attention toward the positive role of reactive oxygen species and positive hole in the photocatalytic reaction [Fig. 11c]. The production of  $\text{OH}^\cdot$  groups under solar irradiation on the CNAg5 surface was recorded by following the intensity of PL emission signals of hydroxyl terephthalic acid at 424 nm [Fig. 11d]. The peak intensity elevates with the increase in the irradiation time, which is taken as evidence for increase in the production of  $\text{OH}^\cdot$  species.

The exceptional photocatalytic reactivity of the as-synthesized samples was attributed to the construction of S-scheme  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  heterojunctions. This novel heterojunction harvests the full broad spectrum and enhances the efficiency of electron-hole pair separation and transportation under solar irradiation. The S-scheme heterojunction is composed of a  $\text{Ag}_2\text{CO}_3$  oxidative photocatalyst and a  $g\text{-C}_3\text{N}_4$  reductive photocatalyst. Upon light illumination, electrons are



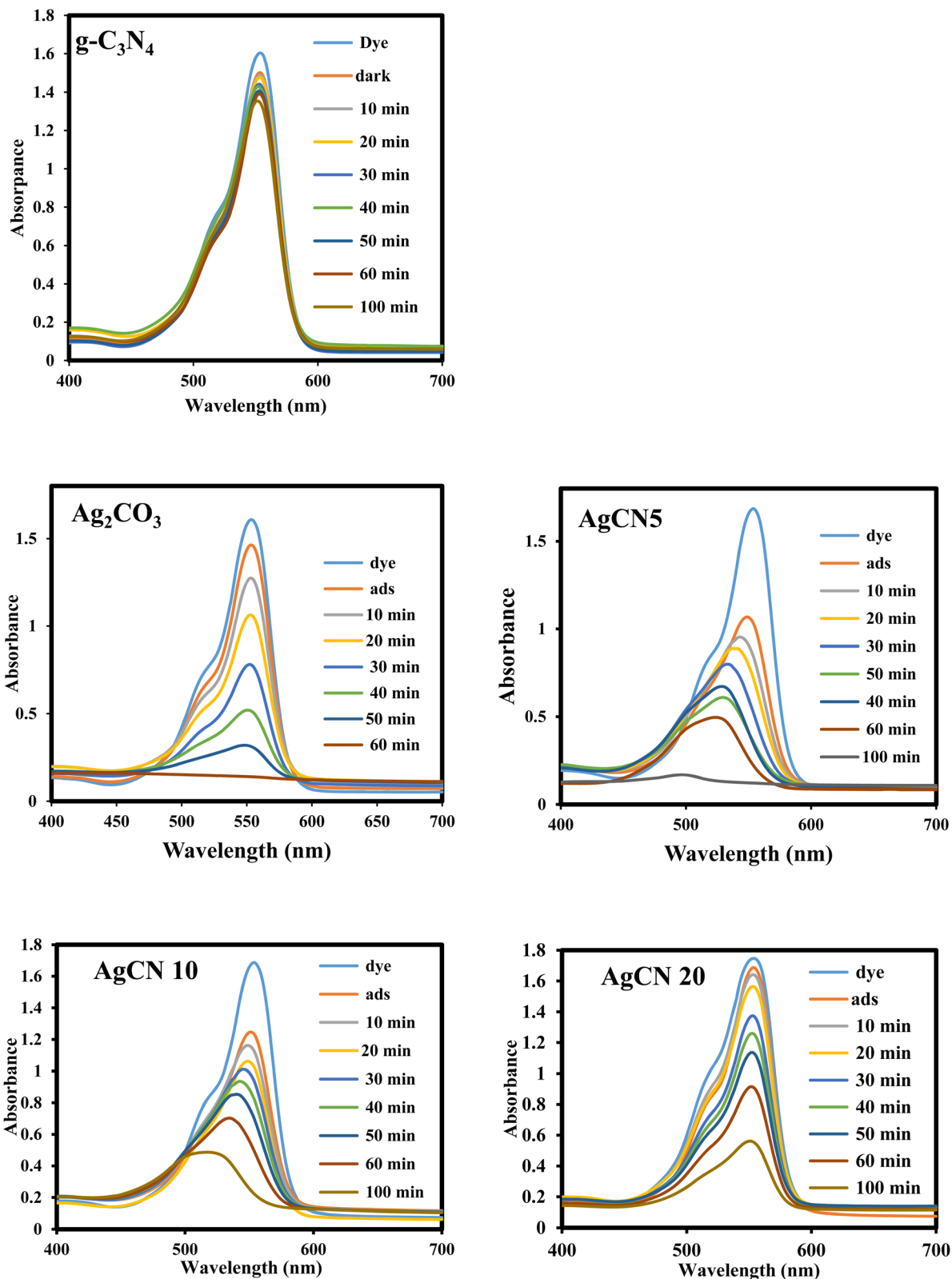


Fig. 10 Absorption spectrum of photodegradation of Rhodamine B dye over  $g\text{-C}_3\text{N}_4$ ,  $\text{Ag}_2\text{CO}_3$ , CNAg5, CNAg10 and CNAg20.

transferred from  $g\text{-C}_3\text{N}_4$  with a greater Fermi level and more negative conduction band potential to  $\text{Ag}_2\text{CO}_3$  with a low Fermi level [Fig. 12]. Concurrently, the Fermi levels of  $\text{Ag}_2\text{CO}_3$  and  $g\text{-C}_3\text{N}_4$

$\text{C}_3\text{N}_4$  photocatalysts jump upward and downward until the two Fermi levels are equalized. The fruitless holes and electrons of  $g\text{-C}_3\text{N}_4$  and  $\text{Ag}_2\text{CO}_3$  respectively are attracted to each other by



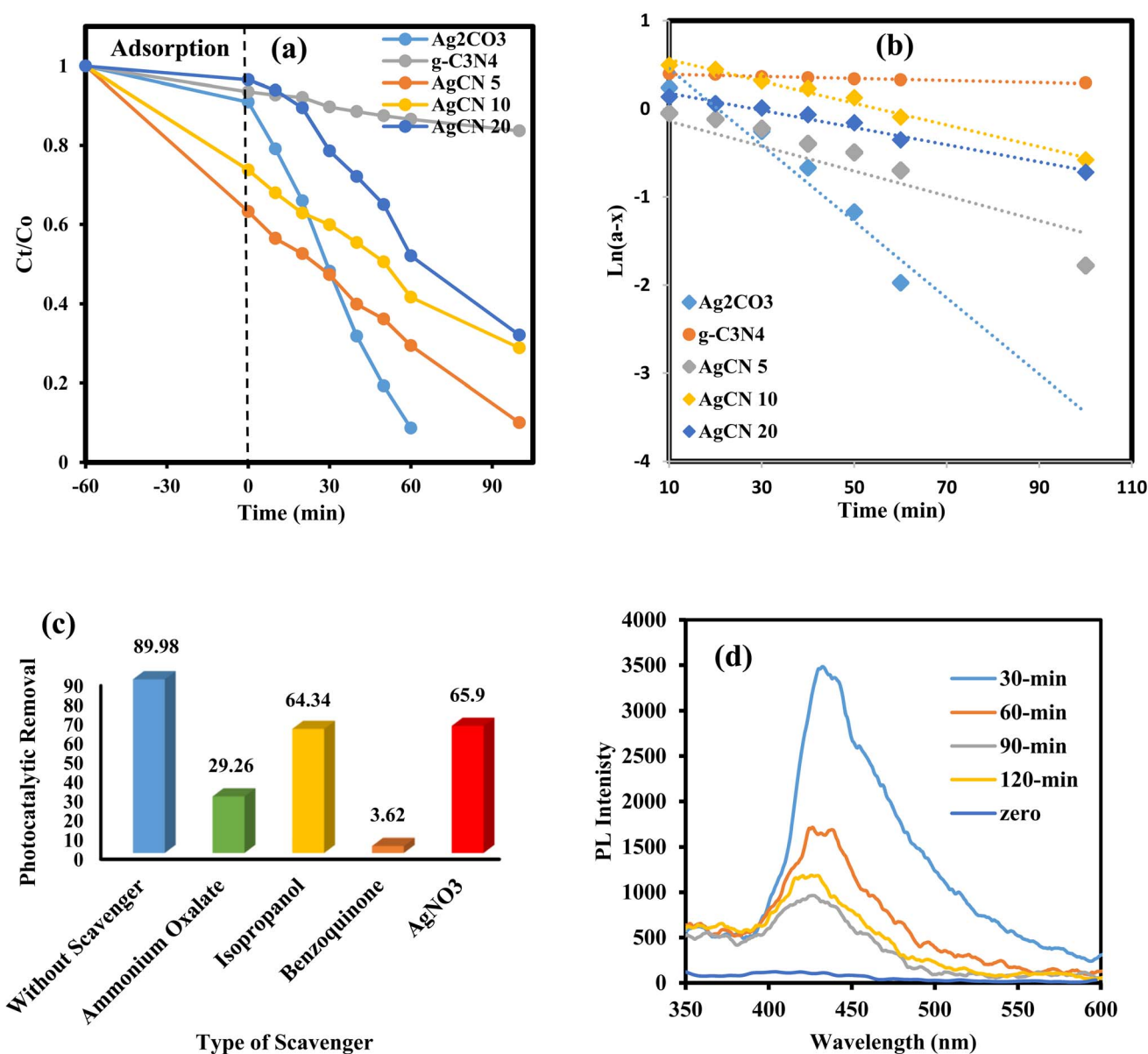


Fig. 11 (a) Variation in the removal of RhB dye over the surface of g-C<sub>3</sub>N<sub>4</sub>, Ag<sub>2</sub>CO<sub>3</sub>, CNAg5, CNAg10 and CNAg20 and the time of irradiation. (b) Pseudo-first order plot for the photodegradation of RhB over the surface of g-C<sub>3</sub>N<sub>4</sub>, Ag<sub>2</sub>CO<sub>3</sub>, CNAg5, CNAg10 and CNAg20. (c) Effect of various scavengers on the photocatalytic degradation of RhB dye over CNAg5 nanocomposites. (d) PL spectrum of terephthalic acid at 315 nm excitation wavelength over CNAg5 nanocomposites against the time of irradiation.

coulombic attraction force and vanished. On the contrary, the hot holes of Ag<sub>2</sub>CO<sub>3</sub> and electrons of g-C<sub>3</sub>N<sub>4</sub> with a higher redox potential were consumed in the photocatalytic process. This mechanism is manifested from the scrubber experiments and the emission PL analysis of hydroxyterephthalic acid. The holes of the valence band of g-C<sub>3</sub>N<sub>4</sub> ( $E_{VB} = 1.5$  eV) and electrons of the conduction band of Ag<sub>2</sub>CO<sub>3</sub> ( $E_{CB} = +0.5$  eV) are useless charge carriers with a weak redox potential and are attracted toward each other by coulombic attraction force and removed leaving a strong built-in internal electric field. On the contrary, the valence band holes of Ag<sub>2</sub>CO<sub>3</sub> ( $E_{VB} = +2.5$  eV) and electrons in the conduction band of g-C<sub>3</sub>N<sub>4</sub> ( $E_{CB} = -1.3$  eV) were consumed

readily in the photocatalytic process. Ag<sub>2</sub>CO<sub>3</sub> positive holes with a potential of 2.55 eV generate hydroxyl radicals ( $E_{OH^-/OH^\cdot} = +2.4$  eV) and electrons in the CB of g-C<sub>3</sub>N<sub>4</sub> with a potential of  $-1.13$  eV generate superoxide radicals ( $E_{O_2/O_2^\cdot} = -0.34$ ). The classical staggered type (II) heterojunction cannot give a true pathway for charge diffusion between oxidative Ag<sub>2</sub>CO<sub>3</sub> and reductive g-C<sub>3</sub>N<sub>4</sub> sheets. The electrons jumping from the conduction band of g-C<sub>3</sub>N<sub>4</sub> to the conduction band of Ag<sub>2</sub>CO<sub>3</sub> fail to produce superoxide radicals ( $E_{O_2/O_2^\cdot} = -0.34$  eV) and the transfer of holes from the Ag<sub>2</sub>CO<sub>3</sub> valence band to the valence band of g-C<sub>3</sub>N<sub>4</sub> cannot oxidize water to produce hydroxyl radicals ( $E_{OH^-/OH^\cdot} = +2.4$  eV). On the basis of the aforementioned





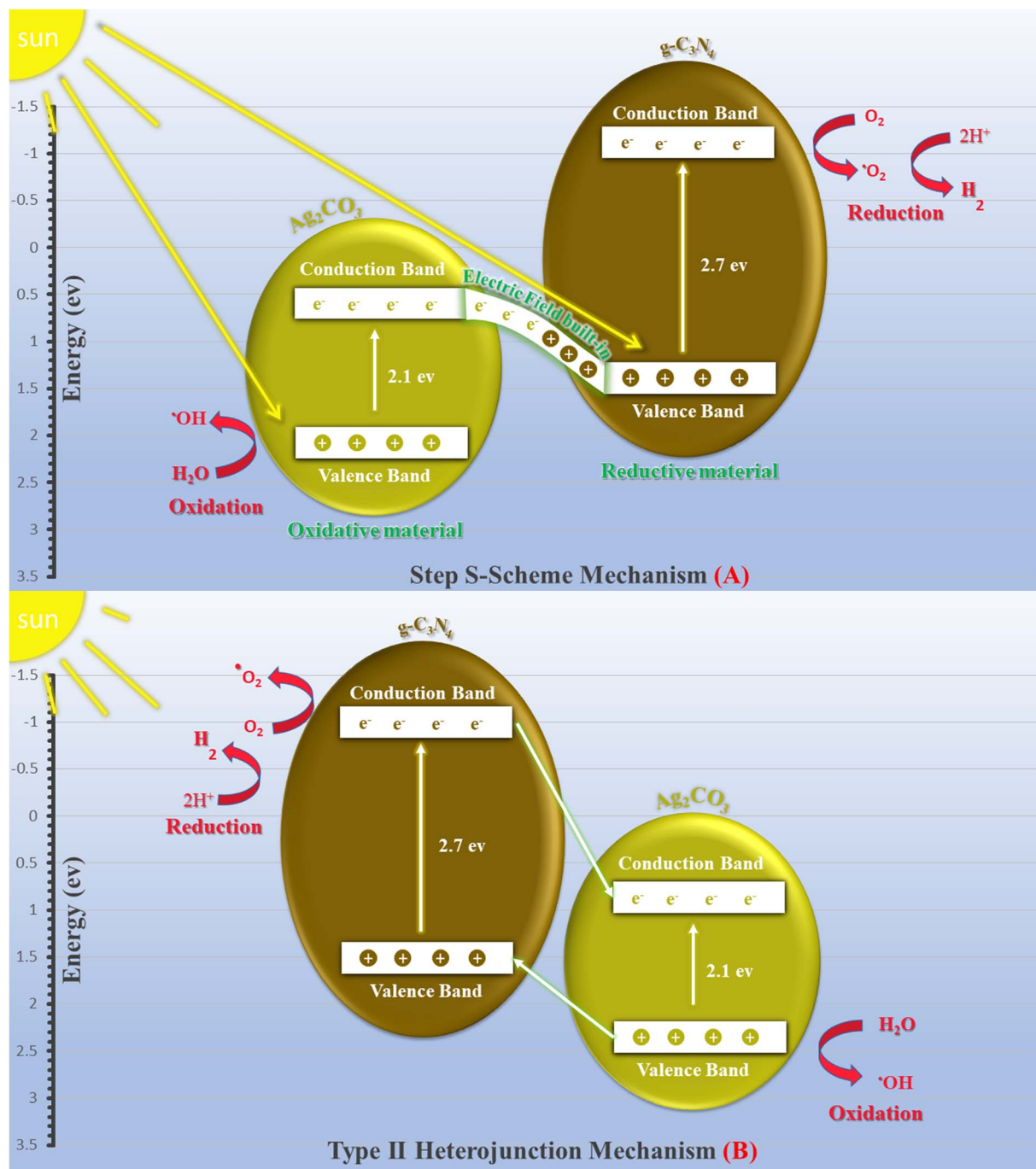


Fig. 12 Scheme for the charge transfer between  $g\text{-C}_3\text{N}_4$  and  $\text{Ag}_2\text{CO}_3$  under natural solar irradiation adopting (a) Step S-scheme mechanism and (b) Type (II) heterojunction.

results, the S-scheme heterojunction is the actual mechanism for explaining the precise charge transportation in the  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  heterojunction. Table 1 provides the comparative study of the decomposition of various organic dyes on the surface of  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  prepared *via* various approaches such as hydrothermal, co-precipitation and sonochemical routes. The results recorded in the previous research studies manifest the requirement of a large proportion of  $\text{Ag}_2\text{CO}_3$  in the nano-composite, which is a negative economic factor due to the large

cost of silver precursors. The mechanism of charge transportation is discussed through the type (II) heterojunction or direct Z-scheme, which fail together in explaining the actual charge migration on the heterojunction surface. On the contrary, our research developed a low-cost and simple sonochemical route for developing  $\text{Ag}_2\text{CO}_3/g\text{-C}_3\text{N}_4$  with 5 wt%  $\text{Ag}_2\text{CO}_3$ , which is efficient to destruct 95% of RhB dye *via* S-scheme heterojunctions.





Table 1 Comparative study

Composite	wt%	Preparation	Pollutant	Source of light	Degradation %	Time (min)	Reference
Ag <sub>2</sub> CO <sub>3</sub> /g-C <sub>3</sub> N <sub>4</sub> g-C <sub>3</sub> N <sub>4</sub> /Ag <sub>2</sub> CO <sub>3</sub>	5%	Sonochemical	Rhodamine B 100 mL, 10 mg L <sup>-1</sup>	Natural sunlight	Rhodamine B 100%, 10 mg of catalyst	100	Our research
	3.5%	Sonochemical	Rhodamine B, methylene blue, 30 mL, 10 mg L <sup>-1</sup>	Xe lamb 500 W	Rhodamine B 100%, methylene blue 100%, 20 mg of catalyst	60	
g-C <sub>3</sub> N <sub>4</sub> /Ag <sub>2</sub> CO <sub>3</sub> Ag <sub>2</sub> CO <sub>3</sub> @/g-C <sub>3</sub> N <sub>4</sub> core-shell	25%	Sonochemical	Rhodamine B, 100 mL 5 mg L <sup>-1</sup>	Xe lamb 300 W	Nearly 100%, 100 mg of catalyst	40	46
	5%	Co-precipitation	Rhodamine B, methylene blue, methyl orange, phenol, 100 mL, 10 mg L <sup>-1</sup>	250 W halide lamp	Rhodamine B above 95% Methylene blue 96% Methyl orange 96.7%	54	47
Ag <sub>2</sub> CO <sub>3</sub> /g-C <sub>3</sub> N <sub>4</sub>	40%	Co-precipitation	Methyl orange, methylene blue, 50 mL, 10 mg L <sup>-1</sup>	Xe lamb 500 W	Phenol 85.5%, 0.1 g of catalyst Methyl orange 93.9%	40	48
	10%	Co-precipitation	Rhodamine B, 250 mL, 5 mg/L	Natural sunlight	Methylene blue 62.8%, 20 mg of catalyst	240	49
Ag <sub>2</sub> CO <sub>3</sub> /g-C <sub>3</sub> N <sub>4</sub> Ag <sub>2</sub> CO <sub>3</sub> /g-C <sub>3</sub> N <sub>4</sub> -MN	7%	Facile precipitation	Methyl orange, 50 mL, 10 mg L <sup>-1</sup>	500 W Xe lamp	100%, 0.1 g of catalyst	30	50
	30%	Facile precipitation	Methyl orange, rhodamine B, 90 mL, 10 mg L <sup>-1</sup>	300 W Xe lamp	Methyl orange, above 95%, 30 mg of catalyst	30	51

## 5. Conclusions

In this research work, S-scheme Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> heterojunctions have been generated by hybridizing different concentrations of spherical Ag<sub>2</sub>CO<sub>3</sub> nanoparticles and g-C<sub>3</sub>N<sub>4</sub> sheets sonochemically for expelling RhB dye. The experimental analysis indicates that the localized deposition of Ag<sub>2</sub>CO<sub>3</sub> on g-C<sub>3</sub>N<sub>4</sub> sheets, deep absorption of solar radiation, better electron hole–electron separation and transportation are the main parameters for optimizing the photocatalytic efficiency of the heterojunction composed of 5 wt% Ag<sub>2</sub>CO<sub>3</sub> and 95% g-C<sub>3</sub>N<sub>4</sub> sheets. The destruction of Rhodamine B dye passes through a series of intermediate organic compounds that finally decompose completely into CO<sub>2</sub> and H<sub>2</sub>O. The charge transportation *via* the S-scheme photocatalytic mechanism was manifested from scrubber trapping experiments and PL analysis of terephthalic acid. Superoxide radicals in addition to positive holes demonstrate a predominant contribution role in degrading Rhodamine B dye under natural sunlight of 500 W intensity.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

The research has been funded by Researchers Supporting Project number (RSP2023R78) King Saud University, Riyadh, Saudi Arabia.

## References

- M. A. Ahmed and Z. M. Abou-Gamra, Mesoporous MgO nanoparticles as a potential sorbent for removal of fast orange and bromophenol dyes, *Nanotechnol. Environ. Eng.*, 2016, **1**(10), 2–11.
- M. Adel, M. A. Ahmed and A. A. Mohamed, Synthesis and characterization of magnetically separable and recyclable crumbled MgFe<sub>2</sub>O<sub>4</sub>/reduced graphene oxide nanoparticles for removal of methylene blue dye from aqueous solutions, *J. Phys. Chem. Solid*, 2021, **149**, 109760.
- M. Adel, M. A. Ahmed and A. A. Mohamed, A facile and rapid removal of cationic dyes using hierarchically porous reduced graphene oxide decorated with manganese ferrite, *FlatChem*, 2021, **26**, 100233.
- M. Adel, M. A. Ahmed and A. A. Mohamed, Effective removal of indigo carmine dye from wastewaters by adsorption onto mesoporous magnesium ferrite nanoparticles, *Environ. Nanotechnol., Monit. Manage.*, 2021, **16**, 100550.
- M. Adel, M. A. Ahmed, M. A. Elabiad and A. A. Mohamed, Removal of heavy metals and dyes from wastewater using graphene oxide-based nanomaterials: A critical review, *Environ. Nanotechnol., Monit. Manage.*, 2022, **18**, 100719.
- A.-N. M. Salem, M. A. Ahmed and M. F. El-Shahat, Selective adsorption of amaranth dye on Fe<sub>3</sub>O<sub>4</sub>/MgO nanoparticles, *J. Mol. Liq.*, 2016, **219**, 780–788.

- 7 J. Joseph, R. C. Radhakrishnan, J. K. Johnson, S. P. Joy and J. Thomas, Ion-exchange mediated removal of cationic dye-stuffs from water using ammonium phosphomolybdate, *Maters Chem. Phys.*, 2020, **242**, 122488.
- 8 M. A. Ahmed, M. A. Ahmed and A. A. Mohamed, Synthesis, characterization and application of chitosan/graphene oxide/copper ferrite nanocomposite for the adsorptive removal of anionic and cationic dyes from wastewater, *RSC Adv.*, 2023, **13**, 5337–5352.
- 9 M. Ghalkhani, N. Zare, F. Karimi, C. Karaman, M. Alizadeh and Y. Vasseghian, Recent advances in Ponceau dyes monitoring as food colorant substances by electrochemical sensors and developed procedures for their removal from real samples, *Food Chem. Toxicol.*, 2022, **161**, 112830.
- 10 S. Ihaddaden, D. Aberkane, A. Boukerroui and D. Rober, Removal of methylene blue (basic dye) by coagulation-flocculation with biomaterials (bentonite and *Opuntia ficus indica*), *J. Water Process. Eng.*, 2022, **49**, 102952.
- 11 M. A. Sayed, M. A. Ahmed, M. F. El-Shahat and I. M. El-Sewify, Mesoporous polyaniline/SnO<sub>2</sub> nanospheres for enhanced photocatalytic degradation of bio-staining fluorescent dye from an aqueous environment, *Inorg. Chem. Commun.*, 2022, **139**, 109326.
- 12 M. Abd Elnaby Wafi, M. A. Ahmed, H. S. Abdel-Samad and H. A. A. Medien, Exceptional removal of methylene blue and p-aminophenol dye over novel TiO<sub>2</sub>/RGO nanocomposites by tandem adsorption-photocatalytic processes, *Maters. Sci. Energy Technol.*, 2022, **5**, 217–231.
- 13 M. S. Hamdy, H. S. M. Abd-Rabboh, M. Beneissa, M. Gad Al-Metwaly, A. H. Glal and M. A. Ahmed, Fabrication of novel polyaniline/ZnO heterojunction for exceptional photocatalytic hydrogen production and degradation of fluorescein dye through direct Z-scheme mechanism, *Opt. Mater.*, 2021, **117**, 111198.
- 14 H. S. M. Abd-Rabboh, M. Beneissa, M. S. Hamdy, M. A. Ahmed and M. Glal, Synthesis of an efficient, and recyclable mesoporous BiVO<sub>4</sub>/TiO<sub>2</sub> direct Z-scheme heterojunction by sonochemical route for photocatalytic hydrogen production and photodegradation of rhodamine B dye in the visible region, *Opt. Mater.*, 2021, **114**, 110761.
- 15 Z. M. Abou-Gamra, M. A. Ahmed and M. A. Hamza, Investigation of commercial PbCrO<sub>4</sub>/TiO<sub>2</sub> for photodegradation of rhodamine B in aqueous solution by visible light, *Nanotechnol. Environ. Eng.*, 2017, **2**, 12.
- 16 A. M. Mohammed, S. S. Mohtar, F. Aziz, M. Aziz and A. Ul-Hamid, Cu<sub>2</sub>O/ZnO-PANI ternary nanocomposite as an efficient photocatalyst for the photodegradation of Congo Red dye, *J. Environ. Chem. Eng.*, 2021, **9**, 105605.
- 17 W. S. Shing, M. J. Hülsey, H. An and N. Yan, Quantum yield enhancement in the photocatalytic HCOOH decomposition to H<sub>2</sub> under periodic illumination, *Catal. Sci. Technol.*, 2022, **12**(16), 5217–5228.
- 18 H. Li and N. Yan, Unlocking the Potential of Photocatalysts in Biomass Refinery, *Chem*, 2020, **6**(11), 2871–2873.
- 19 S. Song, J. Qu, P. Han, M. J. Hülsey, G. Zhang, Y. Wang, S. Wang, D. Chen, J. Lu and N. Yan, Visible-light-driven amino acids production from biomass-based feedstocks over ultrathin CdS nanosheets, *Nature Commun.*, 2020, **11**(1), 4899.
- 20 Y. Wang, L. Yang, R. Zou, J. Lan, A. Yao, H. Xiao and S. Lin, Z-scheme CeO<sub>2</sub>/Ag/CdS heterojunctions functionalized cotton fibers as highly recyclable and efficient visible light-driven photocatalysts for the degradation of dyes, *J. Cleaner prod.*, 2022, **380**, 135012.
- 21 Z. Zheng, F. Han, B. Xing, X. Han and B. Li, Synthesis of Fe<sub>3</sub>O<sub>4</sub>@CdS@CQDs ternary core-shell heterostructures as a magnetically recoverable photocatalyst for selective alcohol oxidation coupled with H<sub>2</sub>O<sub>2</sub> production, *J. Colloid Interface Sci.*, 2022, **624**, 460–470.
- 22 A. Basaleh, A. A. Ismail and R. M. Mohamed, Novel visible light heterojunction CdS/Gd<sub>2</sub>O<sub>3</sub> nanocomposites photocatalysts for Cr(VI) photoreduction, *J. Alloys Compds.*, 2022, **927**, 166988.
- 23 Z. Miao, J. Tao, S. Li, J. Wu, Z. Ding, X. Chen, W. Ma and H. J. Fan, Popcorn-like ZnFe<sub>2</sub>O<sub>4</sub>/CdS nanospheres for high-efficient photocatalyst degradation of rhodamine B, *Colloids Surf., A*, 2022, **654**, 13012.
- 24 A. Ali, A. H. Galal, E. F. El-Sherbeny, A. Soltan, M. F. Abdel-Messih and M. A. Ahmed, Fabrication of S-scheme TiO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> nanocomposites for generation hydrogen gas and removal of fluorescein dye, *Diam. Relat. Mater.*, 2022, **122**, 108819.
- 25 M. Beneissa, N. Abbas, A. A. Saleh, N. Elboughdiri, A. Moumen, M. S. Hamdy, H. S. M. Abd-Rabboh, A. H. Galal, M. Gad Al-Metwaly and M. A. Ahmed, BiVO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> S-scheme heterojunction nanocomposite photocatalyst for hydrogen production and amaranth dye removal, *Optical Mater.*, 2021, **118**, 111237.
- 26 A. F. Amal, A. Ali, A. Soltan, M. G. Elmahgary and M. A. Ahmed, Polyaniline/g-C<sub>3</sub>N<sub>4</sub> hybrid nanoparticles: Fabrication, characterization and boosting bisphenol destruction and hydrogen gas evolution through direct S-scheme aspects, *J. Phys. Chem. Solid*, 2022, **168**, 110773.
- 27 W. Ren, J. Yang, J. Zhang, W. Li, C. Sun, H. Zhao, Y. Wen, O. Sha and B. Liang, Recent progress in SnO<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> heterojunction photocatalysts: Synthesis, modification, and application, *J. Alloys Compds.*, 2022, **906**, 164372.
- 28 A. Balakrishnan, M. Chinthala, R. K. Polagani and D. V. N. Vo, Removal of tetracycline from wastewater using g-C<sub>3</sub>N<sub>4</sub> based photocatalysts: A review, *Environ. Res.*, 2023, **216**, 114660.
- 29 A. Alsalmeh, A. Alfawaz, A. H. Glal, M. F. Abdel Messih, A. Soltan and M. A. Ahmed, S-scheme AgIO<sub>4</sub>/CeO<sub>2</sub> heterojunction nanocomposite photocatalyst for degradation of rhodamine B dye, *J. Photochem. Photobiol.*, 2023, **439**, 114596.
- 30 M. A. Ahmed, F. Ahmed, M. G. Abo-Zaed and E. M. Hashem, Fabrication of novel AgIO<sub>4</sub>/SnO<sub>2</sub> heterojunction for photocatalytic hydrogen production through direct Z-scheme mechanism, *J. Photochem. Photobiol.*, 2020, **400**, 112660.
- 31 N. Al-Zaqri, A. Ali, M. A. Ahmed and A. H. Galal, Construction of novel direct Z-scheme AgIO<sub>4</sub>-g-C<sub>3</sub>N<sub>4</sub> heterojunction for photocatalytic hydrogen production and





- photodegradation of fluorescein dye, *Diam. Relat. Mater.*, 2020, **109**, 108071.
- 32 M. A. Ahmed, B. Mohamed Mahran, A. Mohamed Abbas, M. Ahmed Tarek and A. Mohamed Saed, Construction of direct Z-scheme AgIO<sub>4</sub>/TiO<sub>2</sub> heterojunctions for exceptional photodegradation of rhodamine B dye, *J. Dispersion Sci. Technol.*, 2020, **43**, 349–363.
- 33 A. H. Galal, M. G. Elmahgary and M. A. Ahmed, Construction of novel AgIO<sub>4</sub>/ZnO/graphene direct Z-scheme heterojunctions for exceptional photocatalytic hydrogen gas production, *Nanotechnol. Environ. Eng.*, 2020, **6**, 5.
- 34 M. F. Abdel Messih and M. A. Ahmed, Ayman Soltan, Samy Sobhy Anis; Synthesis and characterization of novel Ag/ZnO nanoparticles for photocatalytic degradation of methylene blue under UV and solar irradiation, *J. Phys. Chem. Solid*, 2019, **135**, 109086.
- 35 P. Raizada, A. Sudhaik, P. Singh, P. Shandilya, P. Thakur and H. Jung, Visible light assisted photodegradation of 2, 4-dinitrophenol using Ag<sub>2</sub>CO<sub>3</sub> loaded phosphorus and sulphur co-doped graphitic carbon nitride nanosheets in simulated wastewater, *Arabian J. Chem.*, 2020, **13**, 3196–3209.
- 36 Z. J. Chen, H. Guo, H. Y. Liu, C. G. Niu, D. W. Huang, Y. Y. Yang, C. Liang, L. Li and J. C. Li, Construction of dual S-scheme Ag<sub>2</sub>CO<sub>3</sub>/Bi<sub>4</sub>O<sub>5</sub>I<sub>2</sub>/g-C<sub>3</sub>N<sub>4</sub> heterostructure photocatalyst with enhanced visible-light photocatalytic degradation for tetracycline, *Chem. Eng. J.*, 2022, **438**, 135471.
- 37 W. An, K. Sun, J. Hu, W. Cui and L. Liu, The Z-scheme Ag<sub>2</sub>CO<sub>3</sub>@g-C<sub>3</sub>N<sub>4</sub> core-shell structure for increased photoinduced charge separation and stable photocatalytic degradation, *Appl. Surf. Sci.*, 2020, **504**, 144345.
- 38 J. Fu, Q. Xu, J. Low, C. Jiang and J. Yu, Ultrathin 2D/2D WO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> step-scheme H<sub>2</sub>-production photocatalyst, *Appl. Catal., B*, 2019, **243**, 556–565.
- 39 Q. Xu, L. Zhang, B. Cheng, J. Fan and J. Yu, S-Scheme Heterojunction Photocatalyst, *Chem*, 2020, **6**, 1543–1559.
- 40 Q. Xu, S. Wageh, A. A. Al-Ghamdi and X. Li, Design principle of S-scheme heterojunction photocatalyst, *J. Mater. Sci. Technol.*, 2022, **124**, 171–173.
- 41 J. Fu, Q. Xu, J. Low, C. Jiang and J. Yu, Ultrathin 2D/2D WO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> step-scheme H<sub>2</sub>-production photocatalyst, *Appl. Catal., B*, 2019, **243**, 556–565.
- 42 L. Zhang, J. Zhang, H. Yu and J. Yu, Emerging S-Scheme Photocatalyst, *Adv. Mater.*, 2022, **34**, 2107668.
- 43 A. M. Basely, M. H. Shaker, F. M. Helmy, M. F. Abdel-Messih and M. A. Ahmed, Construction of Bi<sub>2</sub>S<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> step S-scheme heterojunctions for photothermal decomposition of rhodamine B dye under natural sunlight radiations, *Inorg. Chem. Commun.*, 2023, **148**, 110300.
- 44 A. AlFawaz, A. Alsalmeh, A. M. Alswieleh, M. F. Abdel-Messih, A. H. Galal, M. H. Shaker, M. A. Ahmed and A. Soltan, A low cost and green curcumin/ZnO nanocomposites: Preparation, characterization and photocatalytic aspects in removal of amaranth dye and hydrogen evolution generation, *Opt. Mater.*, 2022, **128**, 112331.
- 45 W. Konglin, Y. Cui, X. Wei, X. Song and J. Huang, The hybridization of Ag<sub>2</sub>CO<sub>3</sub> rods with g-C<sub>3</sub>N<sub>4</sub> sheets with improved photocatalytic activity, *J. Saudi Chem. Soc.*, 2015, **19**(5), 465–470.
- 46 S. Lei, L. Liang, F. Wang, M. Liu and J. Sun, Enhanced visible-light photocatalytic activity and stability over g-C<sub>3</sub>N<sub>4</sub>/Ag<sub>2</sub>CO<sub>3</sub> composites, *J. Mater. Sci.*, 2015, **50**, 1718–1727.
- 47 A. Weijia, K. Sun, J. Hu, W. Cui and L. Liu, The Z-scheme Ag<sub>2</sub>CO<sub>3</sub>@g-C<sub>3</sub>N<sub>4</sub> core-shell structure for increased photoinduced charge separation and stable photocatalytic degradation, *Appl. Surf. Sci.*, 2020, **504**, 144345.
- 48 P. Shugang, B. Jia and Y. Fu, Ag<sub>2</sub>CO<sub>3</sub> nanoparticles decorated g-C<sub>3</sub>N<sub>4</sub> as a high-efficiency catalyst for photocatalytic degradation of organic contaminants, *J. Mater. Sci. Mater. Electron.*, 2021, **32**(11), 14464–14476.
- 49 T. Surendar, S. Kumar and V. Shanker, In situ growth strategy for highly efficient Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> hetero/nanojunctions with enhanced photocatalytic activity under sunlight irradiation, *J. Environ. Chem. Eng.*, 2015, **3**(2), 852–861.
- 50 C. Jiufu, J. Zhong, J. Li, S. Huang, W. Hu, M. Li and Q. Du, Synthesis and characterization of novel Ag<sub>2</sub>CO<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> composite photocatalysts with excellent solar photocatalytic activity and mechanism insight, *Mol. Catal.*, 2017, **435**, 91–98.
- 51 L. Yunfeng, L. Fang, R. Jin, Y. Yang, X. Fang, Y. Xing and S. Song, Preparation and enhanced visible light photocatalytic activity of novel g-C<sub>3</sub>N<sub>4</sub> nanosheets loaded with Ag<sub>2</sub>CO<sub>3</sub> nanoparticles, *Nanoscale*, 2015, **7**(2), 758–764.

